Inverse identification of plastic material behavior using multi-scale virtual experiments

Debruyne[1] D., Coppieters[1] S., Wang[1] Y., Eyckens[2] P., Kuwabara[3] T., Van Bael[2] A.
and Van Houtte[2] P.

[1]Department of Materials Engineering, KU Leuven, Technology Campus Ghent,
Gebroeders de Smetstraat 1, 9000 Ghent, Belgium
[2]Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, 3001 Leuven, Belgium
[3]Division of Advanced Mechanical Systems Engineering, Tokyo University of Agriculture and Technology,2-24-16 Nakacho, Koganei-shi, Tokyo 184-8588, Japan

ABSTRACT

Mixed numerical-experimental techniques used to identify plastic material properties of sheet metal are conventionally based on experimental data (e.g. full-field data) acquired during mechanical experiments. Although those techniques definitely enable to reduce the experimental effort for identifying plastic material properties, accurate identification of advanced phenomenological plasticity models still requires a significant amount of experimental effort. In this paper, we explore the opportunity to further reduce this experimental effort by replacing the mechanical experiments by virtual experiments using a physics-based multi-scale model. To this purpose, the Alamel polycrystal plasticity model, which solely requires the input of the initial crystallographic texture and a single tensile curve, is used to generate virtual plastic work contours in the first quadrant of stress space. The generated virtual experimental data is then used to inversely identify a phenomenological yield function. Finally, the predictive accuracy of the proposed method is investigated by using a finite element code to simulate the hydraulic bulge test.

Key words Multi-scale virtual experiments, anisotropic yield function, differential work hardening, bulge test, sheet metal

INTRODUCTION

This paper deals with phenomenological material models which are widely adopted for numerical analysis and optimization of sheet metal forming operations. The industrial application of advanced phenomenological material models, however, highly depends on the experimental effort to calibrate the governing parameters. Conventionally, these experiments involve proportional loading of the test material with different true stress ratios (σ_x:σ_y). Accurate testing under a fixed stress ratio (σ_x:σ_y) over the large strain range requires the combination of different experiments. Cruciform specimens [1,2] can be used for moderately small plastic strains. Larger strains can be probed using the tube expansion test [3]. The experimental effort required for constructing the plastic work contours consists of number of stress-controlled material tests. Obviously, the accuracy of the identified plastic work contour increases with the number of stress ratios probed. Figure 1 shows an accurate measurement (9 stress ratios in the first quadrant of the stress space are probed) of stress points forming normalized contours of plastic work of mild steel sheet. The experimental effort associated with figure 1 consists of the following material tests: 2 tensile tests (σ_x:σ_y=1:0; 0:1), 7 biaxial tests using cruciform specimens ($\varepsilon_{eq}^{pl} \approx 0.05$ and σ_x:σ_y=2:1; 1:1;3:4;4:3 and 1:2), 7 tube expansion tests ($\varepsilon_{eq}^{pl} > 0.0\ 5$ and σ_x:σ_y=2:1; 1:1;3:4;4:3 and 1:2) and 1 bulge test (σ_x:σ_y=1:1). As such, 17 state-of-the-art material tests are required resulting in quite extensive experimental campaign. Mixed numerical-experimental techniques [4] can be devised to reduce the experimental effort for identifying plastic material properties, however, accurate identification of advanced phenomenological plasticity models still requires a significant amount of experimental effort. In this paper, we explore the opportunity to reduce the experimental effort by replacing the mechanical experiments by virtual experiments using a physics-based multi-scale model. To this purpose, the Alamel polycrystal plasticity model [5], which solely requires the input of the initial crystallographic texture measurement and a single uniaxiale tensile test in 1 direction, is used to generate virtual plastic work contours in the first quadrant of stress space. Indeed, the multi-scale plasticity model can be efficiently employed to generate material response to monotonic loadings under different stress ratios. The model can be used to generate the virtual stress points which can be used to identify phenomenological yield functions. In this contribution, we scrutinize the quality of the contours of plastic work predicted by the multi-scale plasticity model. Additionally, the virtual work contours are used to calibrate the Yld2000-2d yield function [6]. Finally, the identified yield loci are implemented in a finite element code which is used to simulate the hydraulic bulge test.

MATERIAL

In the present study a cold rolled interstitial-free steel sheet with an initial sheet thickness of 0.65 mm is used. This material was characterized in advance using two types of biaxial tensile tests. The cruciform specimen proposed by Kuwabara et al.[1,2] was used to measure the plastic material response in biaxial tension in the moderately small strain range, i.e. equivalent plastic strains up to 0.05. In order to probe larger plastic strains the Multi-axial Tube Expansion Test (MTET) [3] was used. It must be noted that for the stress ratio σ_x:σ_y=1:1 (equibiaxial stress state) fracture occurred at the weld line of the tubular specimen. To cope with this, the work hardening behavior for strains larger than 0.13 was identified using the hydraulic bulge test. Figure 1 shows the normalized plastic work contours associated with different values of the reference true plastic strain ε_0^p. It can be inferred from this figure that in the majority of the stress states the contours of plastic work expand with increase of ε_0^p. Moreover, expansion of the work contours seems to be confined to the initial deformation up to ε_0^p=0.2. The shape of the work contours remains almost constant for 0.2< ε_0^p<0.289. Standard tensile tests (JIS 13 type-B) were conducted to determine the work hardening properties in the rolling direction of the sheet. The Swift hardening, which reads as:

$$\sigma_{eq} = K(\varepsilon_0 + \varepsilon_{eq}^{pl})^n \quad (1),$$

was fitted to the available pre-necking data and the parameters can be found in table 1. In all experiments the von Mises equivalent plastic strain rate was kept constant by approximately $5 \times 10^{-4}\,\frac{1}{s}$.

Parameter	**Value**
K [MPa]	541
$\boldsymbol{\varepsilon_0}$	0.0036
n	0.249

Table 1 : Swift's hardening law fitted to the pre-necking data obtained through a tensile test in the rolling direction

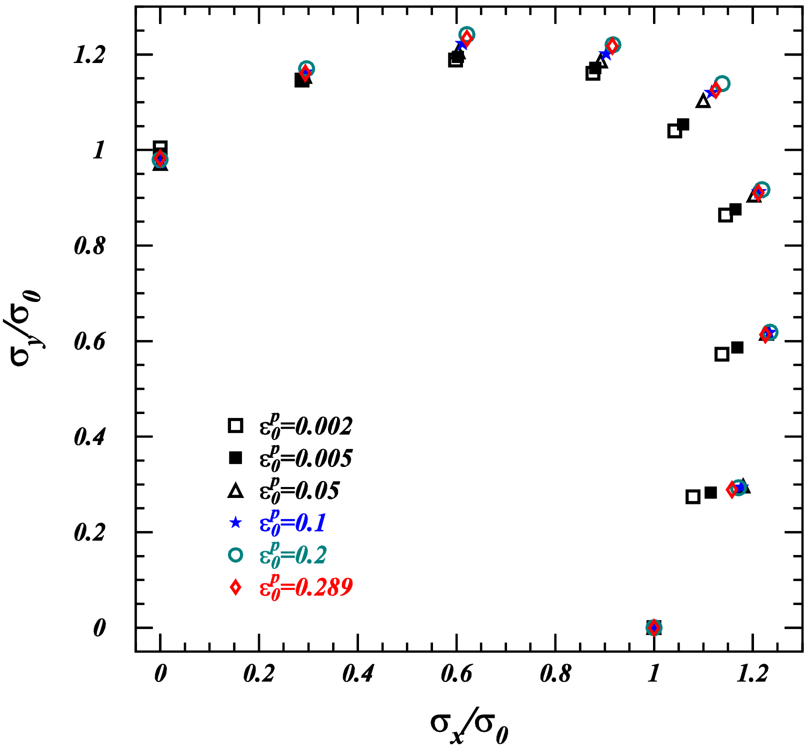

Fig 1. Measured stress points forming normalized contours of plastic work [7]

VIRTUAL MATERIAL TESTS

The Alamel polycrystal plasticity model [5] is used in this section to generate virtual plastic work contours in the first quadrant of stress space. Those calculations are based on a XRD texture measurement of the initial crystallographic texture of the test material. Additionally, the input of a single uniaxial tensile test in 1 direction is required to tune the mirco-Swift hardening law within the multi-scale plasticity model:

$$\tau = k(\Gamma_0 + \Gamma)^n \; (2)$$

where τ and Γ are the critical resolved shear stress of all slip systems and the accumulated slip in a grain, respectively. The parameters of the calibrated micro-Swift hardening law can be found in table 2.

Parameter	Value
k [MPa]	541
$\boldsymbol{\Gamma_0}$	0.00859
n	0.243

Table 2 : Calibrated parameters of the mirco-Swift's hardening law using the Alamel model.

The Alamel model is then employed to generate material response to monotonic loadings under the same 9 different stress ratios as shown in figure 1. As such, 9 virtual experiments are conducted to generate the virtual stress points. Next, the latter data is used to construct the virtual contours of plastic work. To this purpose, the same approach is followed as used to construct the experimentally obtained work contours shown in figure 1. The true stress-true strain curve in the RD was used a reference datum for work hardening. This means that the curve was used to determine the virtual uniaxial true stress σ_0 and the virtual plastic work per unit volume W_0corresponding to particular values of the reference plastic strain ε_0^{pl}. The uniaxial true stress σ_{90} and the biaxial true stress components $(\sigma_x\!:\sigma_y)$ obtained from the virtual experiments were then determined at the same plastic work W_0. Finally, the virtual stress points $(\sigma_0\!:0)$, $(0\!:\sigma_{y90})$ and $(\sigma_x\!:\sigma_y)$ can be plotted in the principal stress space corresponding to a certain value of the reference plastic strain ε_0^{pl}. The experimentally obtained plastic work contours along with the virtually obtained plastic work contours at selected values of ε_0^{pl} are shown in figure 2. In order to quantitatively compare the difference between the shapes of the virtual work contours and the experimentally measured work contours, the following error metric is used:

$$\delta = \sqrt{\frac{\left[\sum_{i=1}^{N}\left(\delta_{i,vir}-\delta_{i,exp}\right)^2\right]}{N-1}} \quad (3)$$

Where $\delta_{i,vir}$ and $\delta_{i,exp}$ are the distances between the origin of the principal stress space and the i^th virtual stress point and experimental stress point, respectively. Figure 3 shows the error metric δ as a function of the reference plastic strain. It can be inferred from this figure that the error metric is larger at the initial deformation, i.e. the first 5%. In other words, at larger plastic strains the shape of the virtual work contours is in closer agreement with the experimentally measured work contours. Although the Alamel model predicts the sufficiently accurate stress levels (see figure 2), a weaker differential work hardening is predicted than experimentally observed, especially in the first 5% plastic strain. Finally, it can be observed from figure 2 that the Swift law Eq.(1) cannot accurately reproduce the initial yield stress.

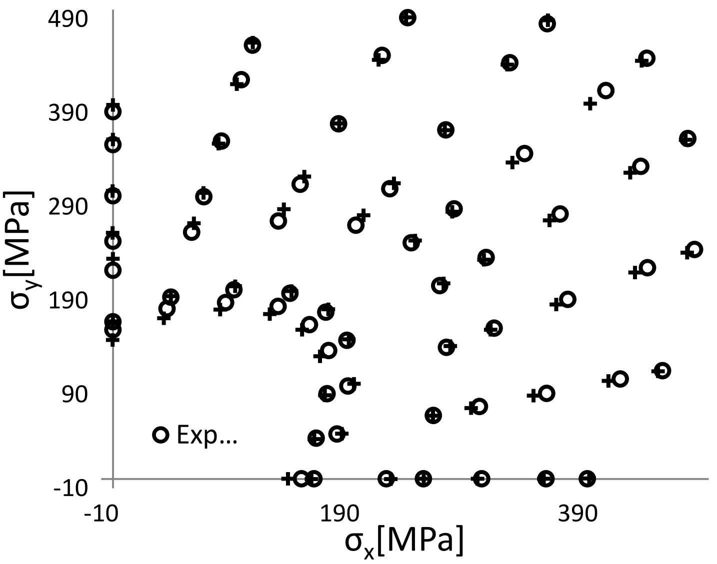

Fig 2. Experimentally and virtually obtained plastic work contours for different values of $\varepsilon_0^{pl} = 0.002; 0.03; 0.1$ and $\varepsilon_0^{pl} = 0.289$

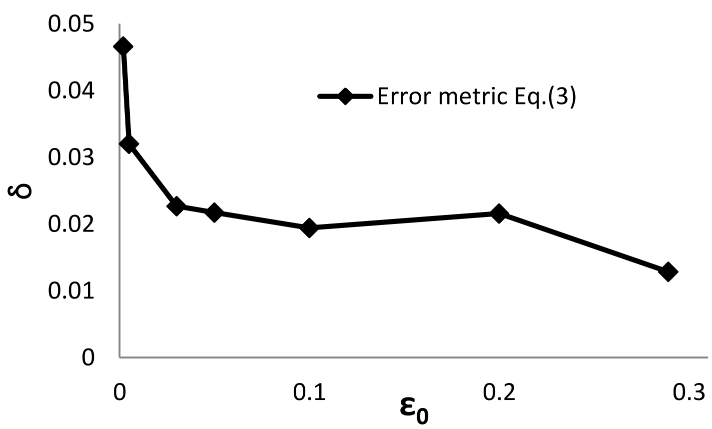

Fig 3. Quantitative comparison of the shapes of the virtual work contours and the measured work contours

FINITE ELEMENT SIMULATION

The plastic work contours from the previous section can be used to identify the parameters of advanced phenomenological yield functions. In this work the Yld2000-2d yield function [6] is adopted and the governing parameters are identified by stress state fitting at different reference plastic strains ε_0^{pl}. Figure 4 shows the virtual stress points along with the fitted Yld2000-2d yield function at different values of ε_0^{pl}.
The ultimate goal of this research is to limit the amount of experimental work associated with the identification of advanced phenomenological yield functions. Clearly, the presented approach can only be of interest if equivalent simulation qualities are achieved, i.e. compared to experimentally calibrated yield functions. To this purpose, the Yld2000-2d yield function was calibrated using experimental data and virtual data predicted by the texture-based Alamel model. Hydraulic bulge tests were performed to quantitatively evaluate the effect of the material models on the predictive accuracy of sheet metal forming simulations.
The test material was characterized up to an equivalent plastic strain of about 0.3. In order to avoid any extrapolation of the acquired material data, the hydraulic bulge test was limited to an equivalent plastic strain of 0.3 at the top of the dome. Potential differential work hardening was ignored and the yield loci were calibrated for a reference plastic of $\varepsilon_0^{pl} = 0.1$. The latter value is more or less the average plastic deformation which can be expected at the top of the dome. The diameter of the die opening was 150 mm with a die radius of 8 mm. The blank diameter was 220 mm and material flow-in was prevented by a draw-bead with a diameter of 190 mm. The hydraulic pressure *P* was controlled so that the equivalent plastic strain rate was constant at $10^{-4}\frac{1}{s}$. The surface strain at the top of the dome was measured using MATCH-3D [8]. Abaqus/Standard was used to simulate the hydraulic bulge test. The FE model contained a blank with a diameter of 190 mm of which the nodal displacements along the edge were assumed to be zero to represent the draw bead. Quad-dominated 4-node shell elements, S4R, were used. The blank holder force of 60 kN was ignored and a coulomb friction coefficient of 0.3 was assumed between the sheet and the blank holder.

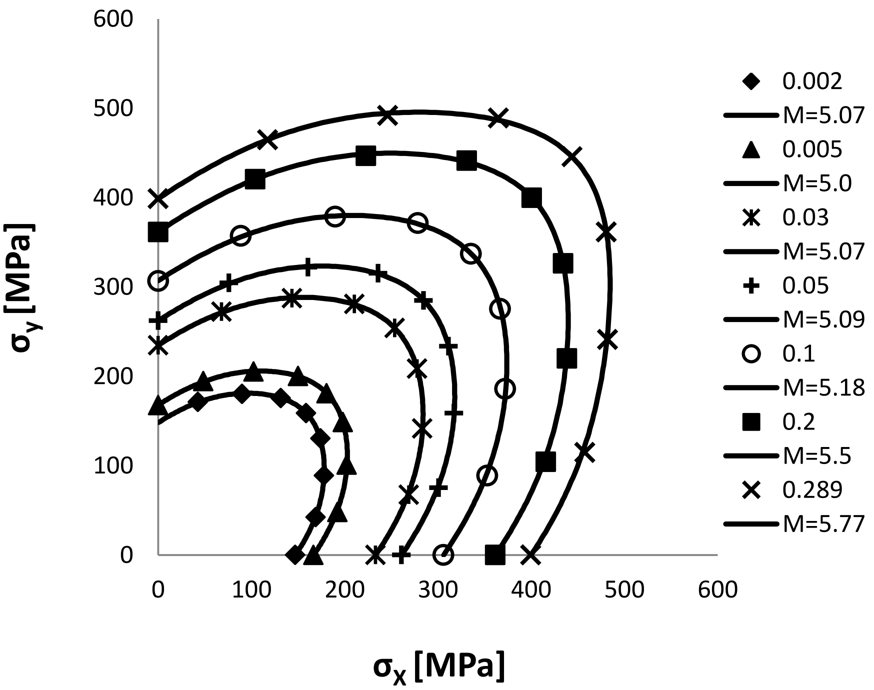

Fig 4. Virtual contours of plastic work for different values of the reference plastic strain ($\varepsilon_0^{pl} = 0.002; 0.005; 0.03; 0.05; 0.1; 0.2;$ and 0.289). M is the exponent of the fitted Yld2000-2d yield function

Figure 5 shows the experimentally measured true thickness strain-pressure curve along with the simulations. It can be observed that all simulations underestimate the maximum pressure. The Yld2000-2d yield function calibrated using experimental data (labeled as *yld2000-2d*) shows the closest agreement with the experiment. The difference, however, with the Yld2000-2d yield function calibrated using virtual plastic work contours (labeled as *yld2000-2d_Alamel*) is small. The latter suggests an equivalent predictive accuracy of both simulations. Figure 5 also shows the results obtained with the von Mises yield criterion. Although the results can be significantly improved by taking in-plane anisotropy into account, the simulations using anisotropic yield functions cannot perfectly reproduce the experimental observations. The result shown in figure 5 can be only slighty improved by taking differental work hardening into account [9].

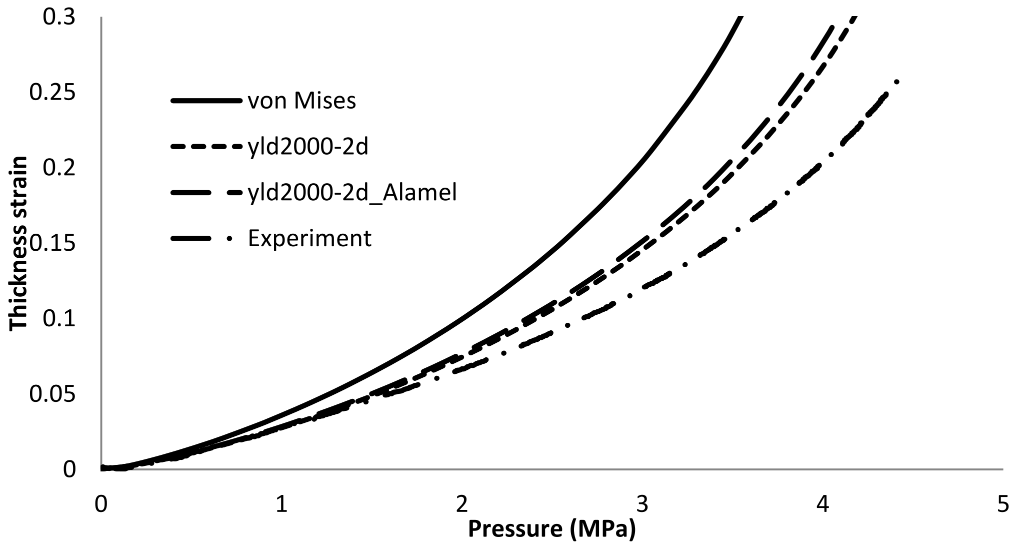

Fig 5. Experimentally measured true thickness strain-pressure curve along simulation results

CONCLUSIONS

In this paper, the opportunity to reduce the experimental effort to identify advanced phenomenological yield functions by replacing the mechanical experiments by virtual experiments using a physics-based multi-scale model is explored. The quality of the contours of plastic work predicted by the multi-scale plasticity model is scrutinized. The predicted virtual work contours are used to calibrate the Yld2000-2d yield function. Hydraulic bulge tests and finite simulations were performed to quantitatively evaluate the predictive accuracy of the proposed method. It has been shown that an equivalent predictive accuracy can be achieved compared to a calibration based on experimentally aqcuired data.

REFERENCES

[1] Kuwabara T., Ikeda S., Kuroda T., Measurement and analysis of differential work hardening in cold-rolled steel sheet under biaxial tension, Journal of Materials Processing Technology, 80-81, pp. 517-523 (1998)

[2] Hanabusa Y., Takizawa H., Kuwabara T., Numerical verification of a biaxial tensile test method using a cruciform specimen, Journal of Materials Processing Technology, 213 pp. 961-970 (2013)

[3] Kuwabara T. and Sugawara F., Multiaxial tube expansion test method for measurement of sheet metal deformation behavior under biaxial tension for large strain range, International Journal of Plasticity 45, pp. 103-118 (2013).

[4] Cooreman S., Lecompte D., Sol H., Vantomme J., Debruyne D., Identification of mechanical material behavior through inverse modeling and DIC. Experimental mechanics, 48 (4), 421-433 (2008).

[5] Van Houtte P., Li S. , Seefeldt M. , Delannay L., Deformation texture prediction: from the Taylor model to the advanced Lamel model, International Journal of Plasticity, 21, pp. 589–624 (2005)

[6] Barlat F., Brem J.C. , Yoon J.W., Chung K., Dick R.E., Lege D.J., Pourboghrat F., Choi S.H., Chu E., Plane stress yield function for aluminum alloy sheets - Part 1: Theory, International Journal of Plasticity 19 pp. 1297-1319 (2003)

[7] Coppieters S., Kuwabara T., Identification of post-necking hardening phenomena in ductile sheet metal, Experimental Mechanics, 54 (8), pp.1355-1371 (2014).

[8] MatchID 3D, http://www.matchidmbc.be/

[9] Ichikawa K., Kuwabara T., Coppieters S., Forming Simulation Considering the Differential Work Hardening Behavior of a Cold Rolled Interstitial-Free Steel Sheet, Key Engineering Materials, 611-612, pp.56-61(2014).